# Space Transportation Main Engine Configuration Study

Contract NAS 8-36867
Configuration Evaluation And Criteria Plan (DR-9)
Volume 2: Evaluation Criteria Plan
August 1986

Prepared For:
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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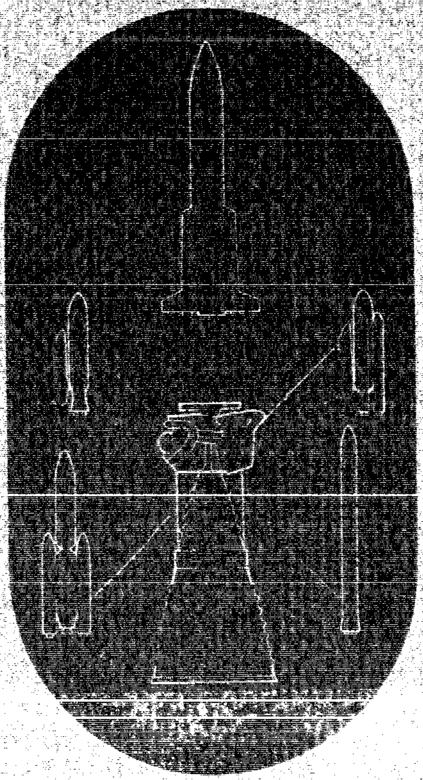

Aerojet
TechSystems
Company

# CONFIGURATION EVALUATION AND CRITERIA PLAN

## VOLUME 2 - EVALUATION CRITERIA PLAN

(PRELIMINARY)

Space Transportation Main Engine

(STME) Configuration Study

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Data Requirement DR-9
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## FOREWORD

This is the Evaluation Criteria Plan for the Space Transportation Main Engine Configuration Study and has been prepared as part of Task 3.0 of Contract NAS8-36867. The work is being performed by the Aerojet TechSystems Company for the NASA - Marshall Space Flight Center.

The program objective is to identify candidate main engine configurations which enhance launch vehicle performance, operation and cost. These candidate configurations will be evaluated and the configuration(s) which provide significant advantages over existing systems will be selected for consideration for the next generation launch vehicles.

The NASA-MSFC Project Manager is Mr. N. Hughes. The ATC Program Manager is Mr. D.C. Rousar and the ATC Study Manager is Mr. E.K. Bair.

The Evaluation Criteria Plan is Volume 2 of the Configuration Evaluation and Criteria Plan, Contract Data Requirement DR-9. Volume 1 is the System Trades Study and Design Methodology Plan.

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## I. INTRODUCTION

The unbiased selection of the Space Transportation Main Engine (STME) configuration requires that the candidate engines be evaluated against a predetermined set of criteria which must be properly weighted to emphasize critical requirements defined prior to the actual evaluation. Since the optimum configuration is a compromise between engine and airframe design, the criteria and relative weighting of the criteria involves a team effort between ATC, MSFC and the Space Transportation Architecture Study (STAS) contractors. The evaluation and selection process, Fig. 1, involves the following functions: (1) determining if a configuration can satisfy basic STME requirements (yes/no) (2) defining the evaluation criteria, (3) selecting the criteria relative importance or weighting, (4) determining the weighting sensitivities and (5) establishing a baseline for engine evaluation. The criteria weighting and sensitivities are cost related and are based on mission models and vehicle requirements. The criteria, weighting and sensitivity will be reviewed for concurrence by MSFC prior to conducting the evaluation process.

The evaluation process is used as a coarse screen to determine the candidate engines for the Task 3 Parametric studies and as a fine screen to determine concept(s) for conceptual design, Task 4. The criteria used for the coarse and fine screen evaluation process is shown in Figure 2.

The coarse screen process involves verifying that the candidate engines can meet the "yes/no" screening requirements and a semi-subjective quantitative evaluation.

The fine screen engines have to meet all of the "yes/no" screening gates and are then subjected to a detailed evaluation or assessment using the quantitative cost evaluation processes. The option exists for re-cycling a concept through the quantitative portion of the screening and allows for some degree of optimization.

The basic vehicle is a two stage LOX/HC, LOX/$LH_2$ parallel burn vehicle capable of placing 150,000 lbs in low earth orbit (LEO). The mission model calls for placement of 800 payloads in LEO starting in the 1995 to 2000 time

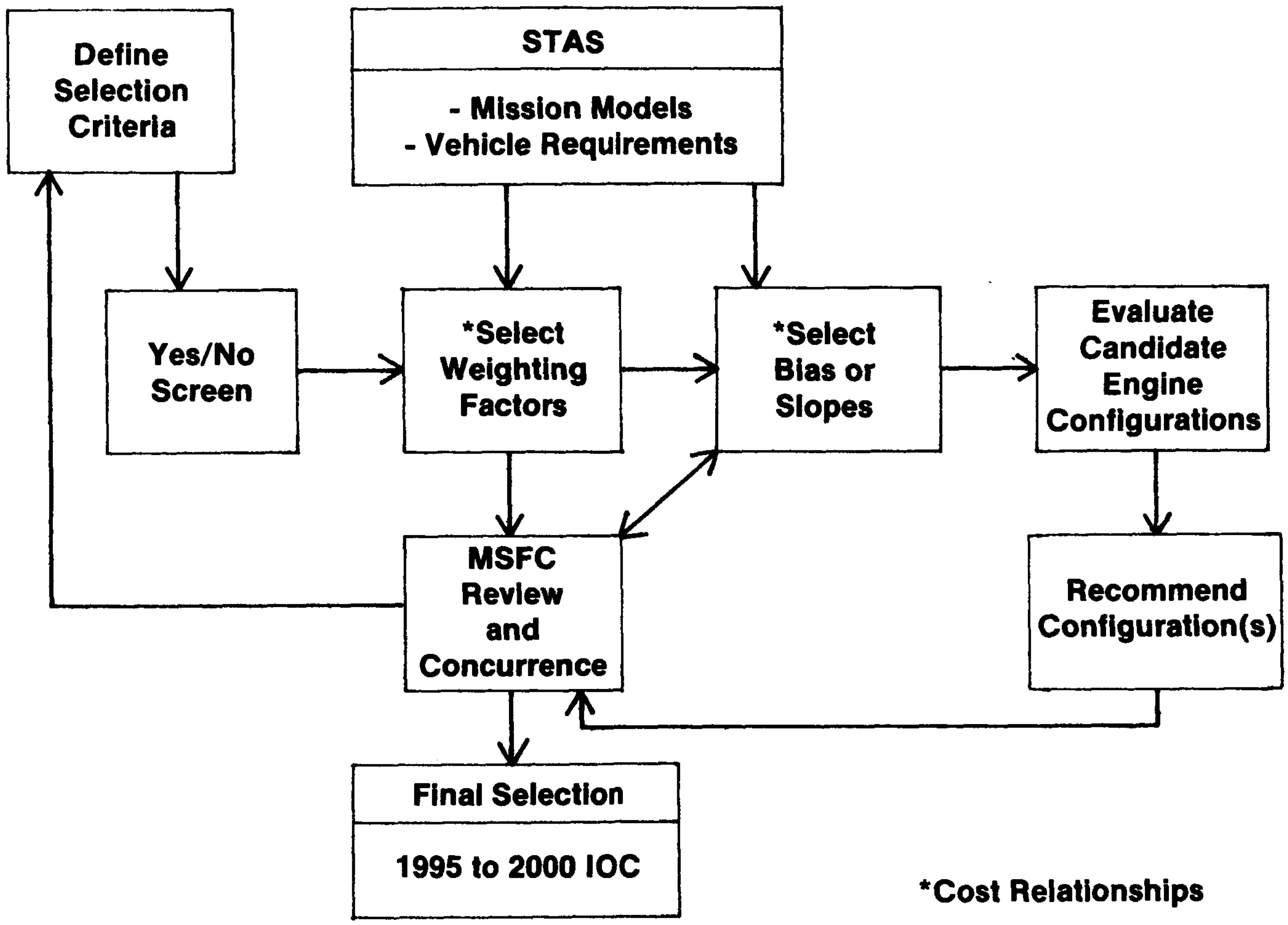



Figure 1. Configuration Evaluation and Selection Plan

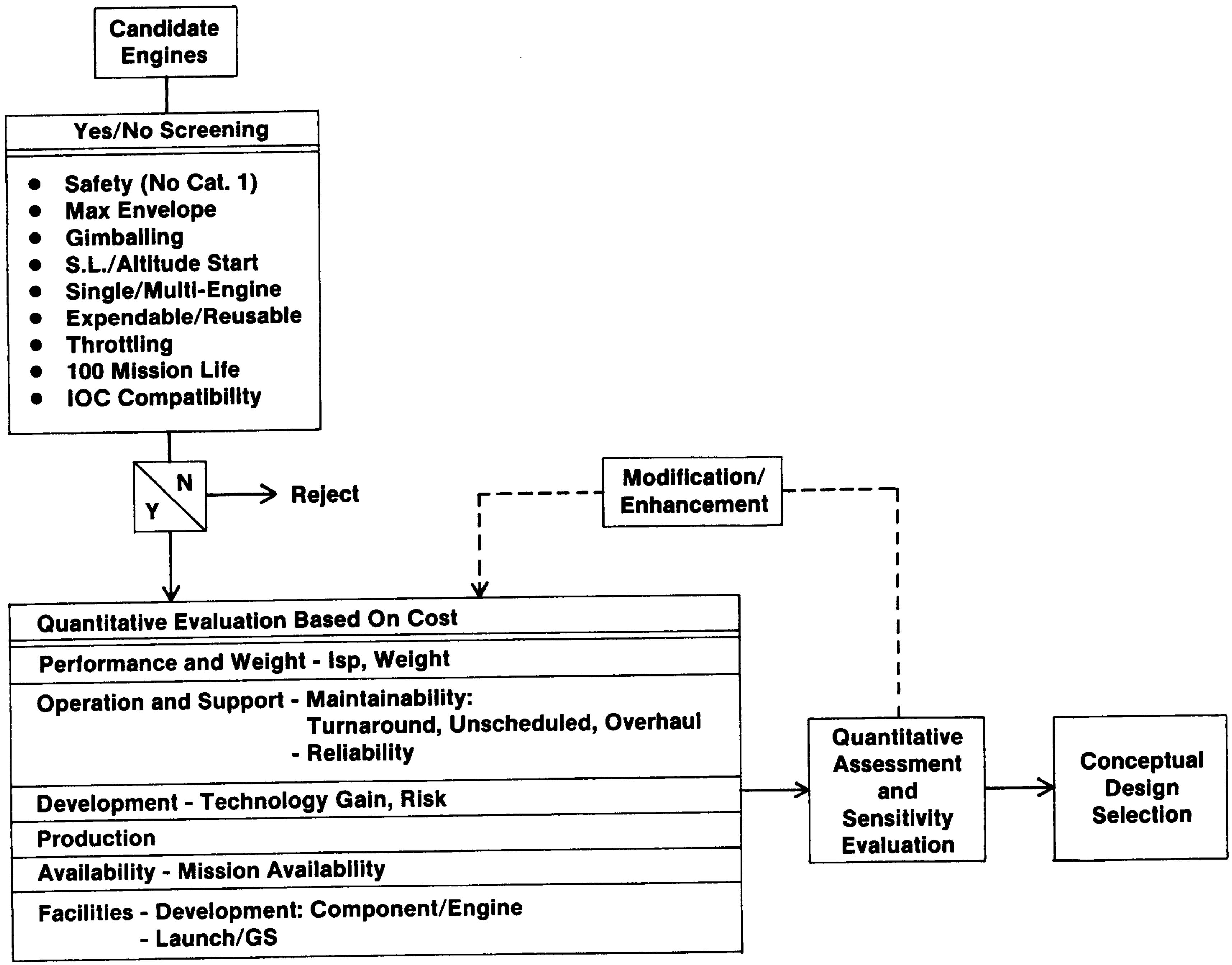



Figure 2. Candidate Engine Screening Process

frame. The 800 missions are to be accomplished with 8 vehicles (100 missions each).

The basic STME is conceived to be a $LOX/LH_2$, 580K (vacuum) thrust engine with a burn time of 520 seconds and a total life of 100 missions.

## II. EVALUATION CRITERIA

The evaluation criteria define the significant functions that are required to properly evaluate an engine system. These criteria include all the significant items covered by the STAS studies in the architecture evaluation as well as items considered significant by ATC. The criteria must allow evaluation from both an engine and vehicle system point of view for proper integration into a complete system. Concepts must pass an initial "yes/no" screening and then are subjected to a quantitative evaluation based on cost.

### A. Yes/No Screen Evaluation

Initially, an engine concept must pass an evaluation relative to "yes/no" type criteria. The concept must be judged as a "yes" in all areas in order to be given further consideration. These criteria are:

Safety
Maximum Envelope
Gimballing Capability
Sea Level and Altitude Start Capability
Single or Multi Engine Application
Expendable or Reusable
Throttling Capability
One Hundred Mission Capability
IOC Compatibility

A positive answer must be given for all of the listed criteria; if it cannot pass these criteria then it has failed to meet the fundamental requirements set down for the STME.

### B. Quantitative (Cost Based) Screen Evaluation

The quantitative criteria screen evaluation is based on cost and is divided into the following six categories: (1) Performance and weight,

(2) Operation and Support, (3) Development, (4) Production, (5) Availability and (6) Facilities. Each category is then further subdivided into subcriteria to allow for a quantitative evaluation (Table I).

Performance and Weight

The performance and weight category includes specific impulse and engine weight. The specific impulse represents a major factor in engine cost and complexity and vehicle system design. The engine propellant, efficiency, cycle, mixture ratio and chamber pressure are the primary factors in determining specific impulse.

Engine weight is dependent on thrust and chamber pressure requirements. The weight is not a totally dominant factor in vehicle design and the airframe contractors are willing to sacrifice some engine weight to enhance operations, reliability and life.

Operation and Support

The operation and support category includes the criteria involved with defining the operations cost of an engine. This includes life and maintainability.

Engine life is dependent on cycle selection and chamber pressure. Higher chamber pressures require higher pump discharge pressures, coolant pressure drop and heat fluxes making it more difficult to maintain life margins.

Maintainability contains the operations and support costs, including turnaround activities, unscheduled maintenance and overhaul requirements.

Turnaround activities include the functions necessary to ready an engine system from flight to flight. This activity is the major contributor to the operation and support category. The following activities are considered in

TABLE I

Quantitative Evaluation Criteria

| Category | Criteria | Subcriteria |
| --- | --- | --- |
| Performance and Weight | Isp<br>Weight | |
| Operation & Support | Maintainability<br>Safety & Reliability | Turnaround<br>Unscheduled<br>Overhaul |
| Development | Development Time, Risk, and Cost | |
| Production | | |
| Availability | Mission Availability | |
| Facilities | Development | Component<br>Engine |
| | Launch/GSE | |

the turnaround evaluation: leak checks, diagnostics, boroscope inspections, pump torque checks, injector inspection, gas generator/preburner inspection, turbine system inspection and coolant system inspection.

Unscheduled maintenance is dependent on relative engine complexity and cycle selection. Some configurations can lead to increased susceptibility to component replacements prior to engine overhaul.

Engine overhaul is dependent on the engine cycle selection and configuration. Engine cycle and chamber cooling methods determine the extent of inspection and replacement requirements.

Reliability is dependent upon the engine's ability to meet its performance and operational design requirements. It is the composite result of establishing adequate design margins and the ability to predict the engine loading and operating environments.

<u>Development</u>

The development category includes the factors that determine the DDT & E costs for developing an engine system. Engine cycle, thrust level, chamber pressure, propellant selection and life are important factors in determining development costs. Additionally, technology availability and development risk must be considered in this category. Only engines which can be developed in the required time will be given further consideration.

<u>Production</u>

The production category includes the factors that determine the production cost of an engine system. Engine cycle, thrust level, chamber pressure and the number of engines produced are used to determine production costs. The number of engines produced is also a function of engine life.

II, Evaluation Criteria (cont.)

## Availability

Availability is a reflection of the engine system's reliability and is considered in this evaluation as a measure its ability to meet the mission needs on time. An availability value of 98% was used in establishing this criteria.

## Facilities

The facilities category determines the development and launch/ground support requirements for the engine development, acceptance and use. The development facilities are dependent on engine cycle propellants and chamber pressure. The launch and ground support criteria is dependent on propellant selections and engine cycle.

## III. "YES/NO" EVALUATION CRITERIA

As discussed in Section II, the initial engine evaluation is a "yes/no" screening which requires that a concept pass every element in the criteria to be considered further. The process is shown graphically in Fig. 3.

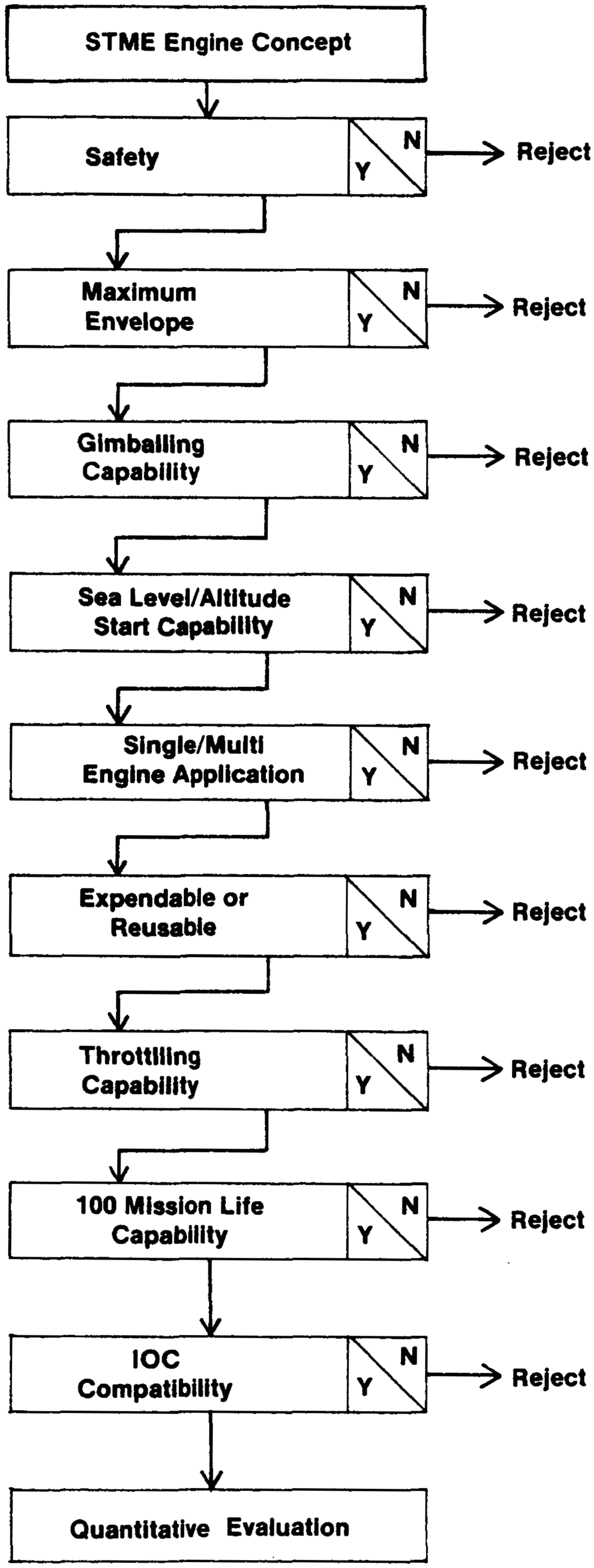



**Figure 3. "Yes/No" Screening Process**

## IV. QUANTITATIVE CRITERIA WEIGHTING

The mission model assumed for use in developing the quantitative evaluation criteria uses an eight vehicle fleet, each capable of 100 missions. The first mission occurs between 1995 and 2000. For the upper stage, two 580,000 lbf (vacuum) engines are assumed with a burn time totalling 520 seconds for each mission.

For use in the evaluations, it was assumed that combined capability of existing NSTL and other (new or existing) facilities would be in place and operation in time to support the STME development, qualification and production acceptance test schedule demands.

The quantitative criteria weighting represents the relative importance of the defined categories and criteria used to evaluate an engine system. The STAS contractors recommend costing the criteria categories to establish their relative importance, and this is the procedure which will be used. The cost values for each category are shown in Table II and were estimated, in part, using ATC's Cost Estimating Relationships (CER) developed for the STAS contractors with the NASA-MSFC supplied mission model. The STAS equations were used for development and production cost estimates. The performance and weight criteria are based on the effect of Isp and engine weight. The performance and weight cost is determined based on the potential loss of revenue due to a lower performing engine (-10 sec max) and the impact of added engine weight (1600 lbs, max, total). Because of added propellant or engine weight, a corresponding payload loss is incurred with an attendant loss in revenue. This is applied across the entire mission model. The costs represent the worst case.

The operations and support evaluation criteria are based upon scheduled and unscheduled maintenance costs and overhaul costs as reflected by life and start capability and reliability/cost effects. The scheduled and unscheduled maintenance costs reflect Space Shuttle derived values while the overhaul value is based on historic Titan data. Reliability, relative to meeting operational goals, is treated as a bias on the total (sum) operation costs,

TABLE II

Category Cost* and Weighting

| Category | Cost | Weighting Value (Rounded) |
| --- | --- | --- |
| Performance and Weight | 3.6 Billion | 25% |
| Operation and Support | 5.4 Billion | 40% |
| Development | 3.0 Billion | 20% |
| Production | .7 Billion | 5% |
| Availability | 1.2 Billion | 8% |
| Facilities | .2 Billion | 2% |
| | 14.1 Billion | 100% |

* Cost values reflect worst case engine
(Scores zero in weighting value analysis)

i.e., a .9 operations reliability will impose an additional (1-R)=10% on the operations costs. The facility costs were estimated assuming the construction of five engine test stands, an engine component test facility for pump, chamber and GC/preburner development and GSE requirements. The availability category was estimated using the probability that the launch system could successfully meet its schedule and delivery requirements.

After developing a cost for each category as discussed above, a percentage of the total cost was assigned to each category. The individual category costs and weighting are shown on Table II. Each of the criteria and subcriteria was similarly subdivided based on cost. The nominal value for each criteria is shown in Figure 4 which also shows the format for quantitative evaluation of the individual criteria and engine concepts.

Once the criteria weighting is established, the sensitivity of the criteria is required. The sensitivity is the unit change per unit criteria weight. The first step is to determine the total range of variation in the criteria for the engines considered. This range is then evaluated against the criteria weight. The ratio of range/wt is the sensitivity to variations. A linear variation in weight is assumed for the range of each criteria considered.

## Performance

The weighting for the performance criteria is based on the impact the variation in performance will have on payload delivery capability. In this case, a total performance variation of 10 seconds of Isp was assumed. Using a modified $\Delta V$ requirement, which accounts for gravity, drag and thrust losses, and an assumed lift-off thrust to weight ratio of 1.3, the propellant difference imposed by the 10 second performance variations was determined. This was converted to equivalent payload assuming a \$500/lb to LEO delivery cost.

| Evaluation Criteria | | | Weighting Maximum Value | Engine Concepts | | | |
|---|---|---|---|---|---|---|---|
| Performance & Weight | Isp | | 21 | | | | |
| | Weight | | 4 | | | | |
| Operation & Support | Maintainability | Normal Turnaround | 10 | | | | |
| | | Unscheduled | 18 | | | | |
| | | Overhaul | 8 | | | | |
| | Reliability | | 4 | | | | |
| Development | | | 20 | | | | |
| Production | | | 5 | | | | |
| Availability | | | 8 | | | | |
| Facilities | Development | | 1 | | | | |
| | Launch/GS | | 1 | | | | |
| | | Total | 100 | | | | |

Figure 4. Candidate Engine Evaluation Format

IV, Quantitative Criteria Weighting (cont.)

The cost effect of engine weight was based on a potential total engine weight variance of 1600 lbs. This was then equated to loss of payload.

The effect of performance and weight variation was found to amount to 25% of the total weighting score (100), with Isp performance being 21% and weight being 4%. The performance evaluation criteria is graphically shown in Fig. 5

## Operation and Support

The weighting for the operation and support category, shown in Figure 6, is based on historic Space Shuttle data for the SSME for scheduled and unscheduled maintenance and Titan for overhaul.

The normal turnaround maintenance costs were determined to have a weighting value of 10 and unscheduled maintenance, 18. Using historic Titan data on overhaul (complete) resulted in a weighting of 8 for this category. The overhaul value is based on a twenty-five mission between overhaul basis.

The reliability is based on a lower limit of .9. This value is based upon the engine ability to meet operational needs and is not meant to reflect reliability relative to structural failures.

The Operation and Support Evaluation is shown in Fig. 6 and a breakdown of turnaround and unscheduled maintenance item is shown in Table III.

## Development

The weighting for the development criteria is based on the STME DDT & E cost equations for developing a 580K lbf thrust engine. The cost equations use propellant, thrust and chamber pressure for cost estimates. The maximum DDT & E cost for a 580K STME is approximately $3 billion which equates to a criteria weight of 20.

| Evaluation Criteria | | Maximum Weighting Value |
|---|---|---|
| Performance | Isp | 21 |
| | Weight | 4 |

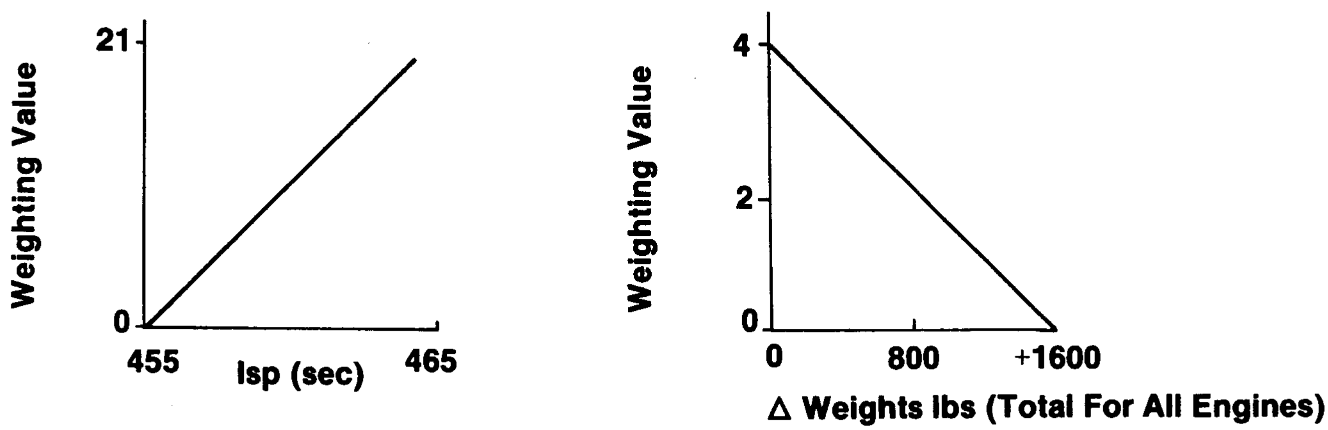
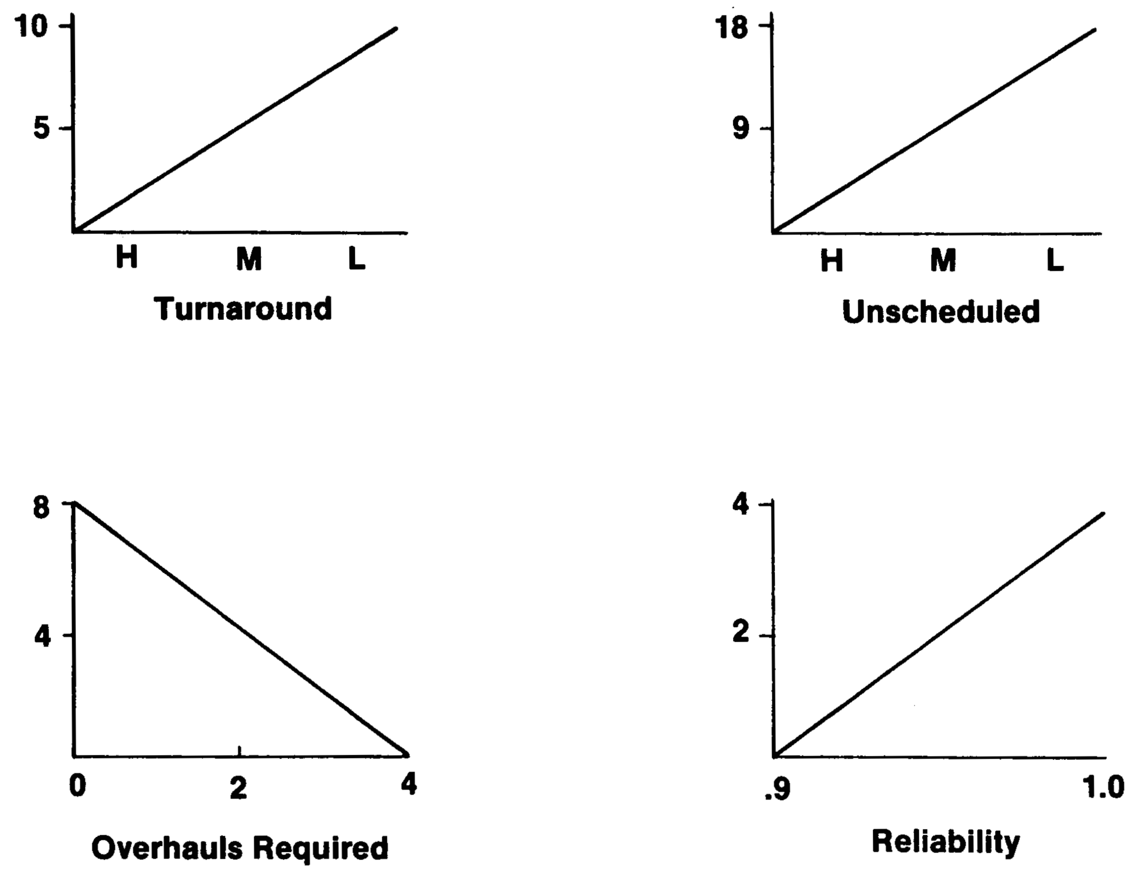



Figure 5. Performance Criteria Evaluation

| Evaluation Criteria | | | Maximum Weighting Value |
|---|---|---|---|
| Operation and Support | Maintainability | Turnaround | 10 |
| | | Unscheduled | 18 |
| | | Overhaul | 8 |
| | Reliability | | 4 |




Legend
L Low
M Medium
H High

Figure 6. Operation and Support Evaluation

TABLE III

Turnaround and Unscheduled Activity Evaluation

| | | Task Complexity | | | | |
|---|---|---|---|---|---|---|
| Turn Around Activity | Max. Value | VL | L | M | H | VH |
| Leak | 2 | | | | | |
| Diagnostic | 2 | | | | | |
| Boroscope | 2 | | | | | |
| Torque | 2 | | | | | |
| Cleaning | 2 | | | | | |
| | 10 | | | | | |
| Unscheduled Activity | | | | | | |
| Remove/Install Engine | 5 | | | | | |
| Inspect for Foreign Objects | 5 | | | | | |
| Discoloration/Distortion | 4 | | | | | |
| Damage Evaluation/Repair | 4 | | | | | |
| | 18 | | | | | |

Legend

VL - Very Low 5 pts

L - Low 3 pts

M - Medium 2 pts

H - High 1 pt

VH - Very High 0 pts

Each engine configuration will be cost estimated using the basic equations supplied to the STAS contractors.

The STAS equation for a cryogenic propellant engine for DDT & E is based on historic data and is expressed as:

$$3.7274 \times 10^{4} \; [1 + 5 \times 10^{-5} \; (Pc\text{-}1000)] \; T^{.305}$$

For a 580K, 3200 psi Pc engine, the basic DDT & E is estimated to be $\$2.4 \times 10^{9}$. This value is then modified to account for required technology gains and a risk assessment.

The technology gain is based on an advancement from a technology level of 4 (Critical Function/Characteristics Demonstrated) to a level 6 (Prototype/Engineering Model Testing in Relevant Environment) and the risk level is assumed to be medium (6): (1) Technology exists but has never been demonstrated, (2) Alternatives are possible but are costly in terms of dollars, and (3) Resources and schedules are marginal for parallel development but parallel developments are still possible. The resulting multiplier on this basic is approximately 1.25 making the maximum expected DDT & E $\$ 3 \times 10^{9}$, with a weighting value of 20.

The development evaluation criteria is shown in Fig. 7.

## Production

The production costs are based on a total engine assembly demand of twenty engines.

| | | | | |
|---|---|---|---|---|
| Flight: | 8 Vehicles, 2 Engines/Vehicle | = | 16 | |
| | 2 Qualification Engines | = | 2 | (Vehicle System) |
| | 2 Spare Engines | = | 2 | |
| | Total | = | 20 | |

| Evaluation Criteria | Maximum Weighting Value |
| --- | --- |
| Development | 20 |

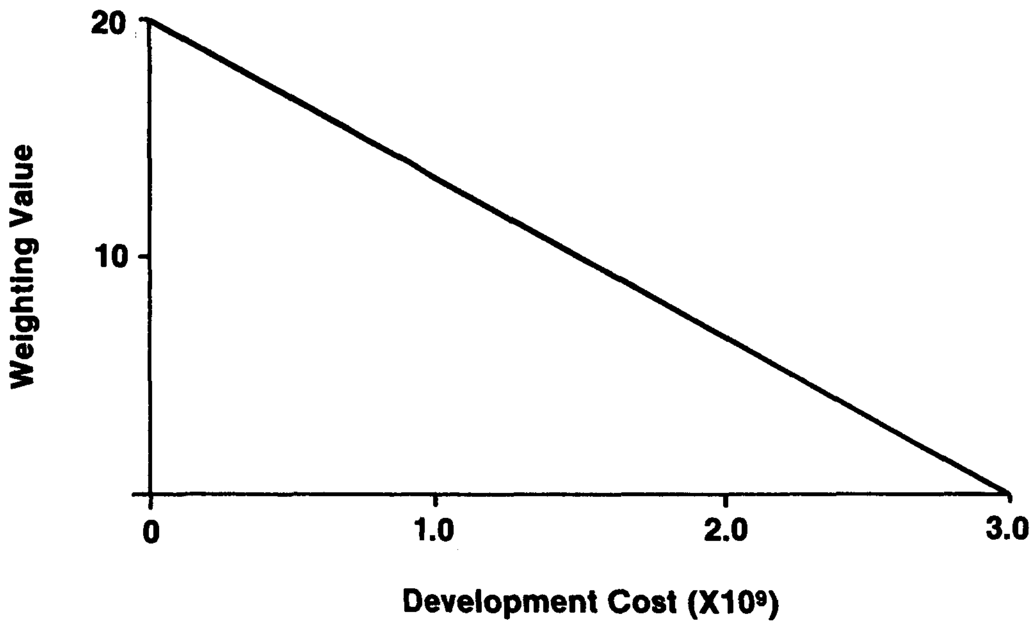



Figure 7. Development Evaluation

Since the SSME is probably close to the STME in size its approximate production cost was used to establish the upper end of the STME production cost. The SSME production cost per engine was set at $\$35 \times 10^6$. The resulting STME production cost was found to be $\$.7 \times 10^9$ which has a weighting value of 5. The production evaluation relationship is shown in Figure 8.

## Availability

The availability criteria is based on the assumption that the vehicle, based on STME availability, can meet the launch schedule a minimum of 98% of the time. The 2% unavailability is a loss and equates to a weighting value of 8 when considered as loss of revenue. The availability evaluation criteria is shown in Fig. 9.

## Facilities

The weighting for the facility category is based on the cost of the new facilities involved with the development and launch support of the STME. These costs are estimated to be approximately $200 million which would yield a relative weight of 2.

The development facilities are divided into two areas component and engine. The engines are rated on the level of component testing that can be accomplished and on the complexity of the engine testing. Gas generator cycles are ranked higher than staged combustion cycles for component level testing because the hardware can be tested at the component or subassembly level prior to engine level testing. Also, a configuration that allows for component level testing and maturity prior to engine level testing would be ranked higher than systems that had little maturity prior to engine level testing.

The launch and ground support criteria is a function of the propellant handling requirements and system complexity, Fig. 10.

| Evaluation Criteria | Maximum Weighting Value |
|---|---|
| Production | 5 |

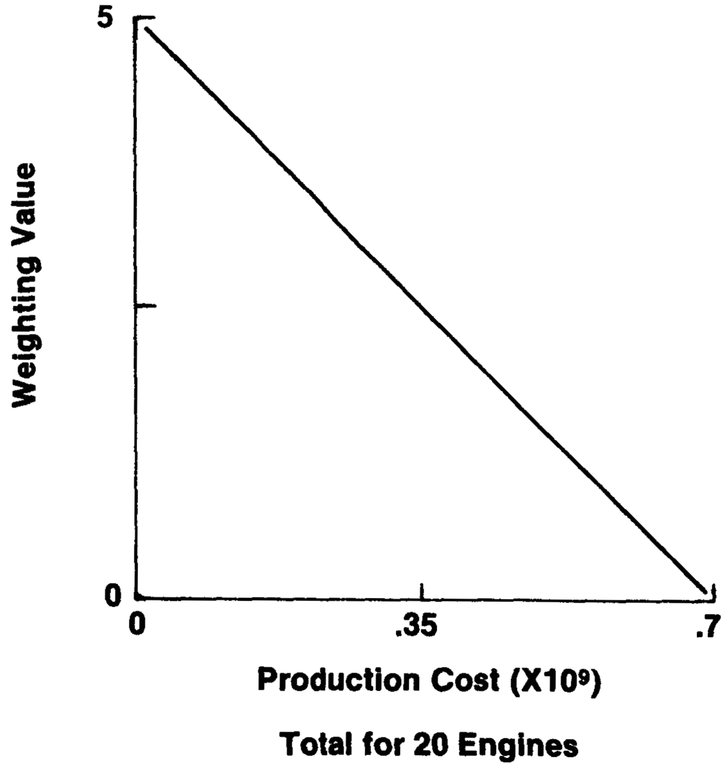



Figure 8. Production Criteria Evaluation

| Evaluation Criteria | Maximum Weighting Value |
|---|---|
| Availability | 8 |

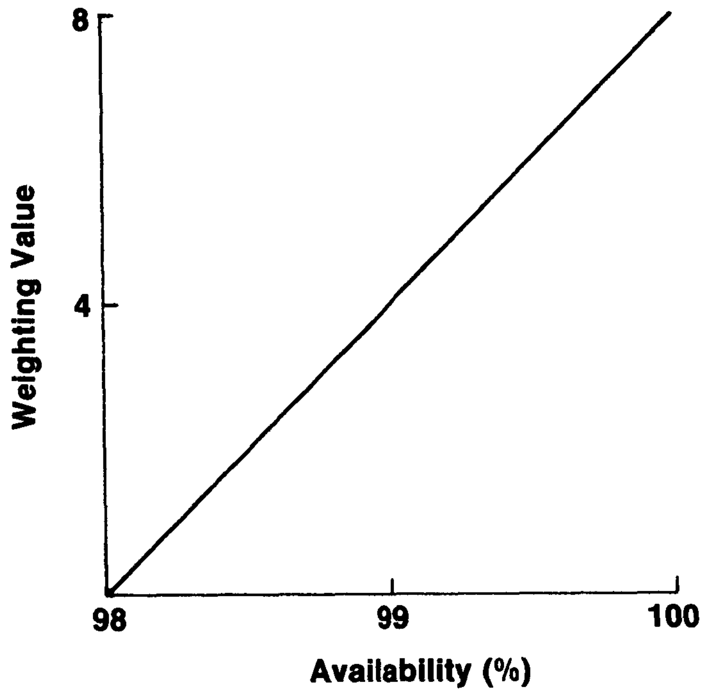



**Figure 9. Availability Criteria Evaluation**

| | Evaluation Criteria | Maximum Weighting Value |
|---|---|---|
| Facilities | Development : Component & Engine | 1 |
| | Launch/GS | 1 |

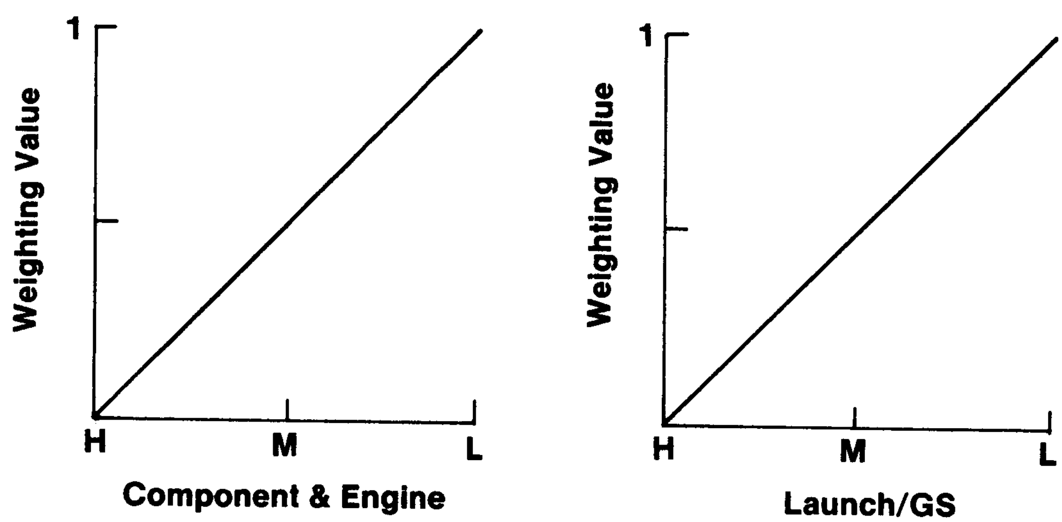



Figure 10. Facilities Criteria Evaluation

## V. BASELINE ENGINE

The optimum engine is represented by the addition of the weighting values for each criteria, which totals 100 points maximum. This represents an engine design which provides the highest performance for the lowest price with the lowest operation and support costs. Rating the engines against the maximum value for a given category results in obtaining a clear perspective on the relative strengths and weaknesses of a given candidate configuration.